

# En-Route Care in the Air: Snapshot of Mechanical Ventilation at 37,000 Feet

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**Objective:** En-route care necessitates the evacuation of seriously wounded service members requiring mechanical ventilation in aircraft where low light, noise, vibration, and barometric pressure changes create a unique clinical environment. Our goal was to evaluate ventilatory requirements, oxygenation, and oxygen use in flight and assess the feasibility of a computer interface in this austere environment.

**Methods:** A personal computer was integrated with the pulse oximeter and ventilator data port used in aeromedical evacuation from Iraq to Germany. Ventilator settings, inspired oxygen ( $\text{FiO}_2$ ), tidal volume ( $V_T$ ), respiratory rate (RR), minute ventilation ( $V_E$ ), monitored values, heart rate (HR), and oxygen saturation ( $\text{SpO}_2$ ), were recorded continuously. Oxygen use was determined using the equation  $([\text{FiO}_2 - 21]/79) \times (\text{MV}_E)$ . Additional data were obtained through the United States Air Force (USAF) Transcom Regu-

lation and Command/Control Evacuation System (TRAC2ES) and the United States Army Institute of Surgical Research Joint Theater Trauma Registry databases.

**Results:** During a 4 month time frame 117 hours of continuous recording was accomplished in 22 patients. Mean age was  $27 \pm 9.83$  and injury severity score military was  $31.75 \pm 20.63$  (range, 9–75). All patients survived transport. Mean values for ventilator settings were  $\text{FiO}_2$  (24–100%) of  $49\% \pm 13\%$ , positive end-expiratory pressure of  $6 \pm 2.5$  (range, 0–17 cm  $\text{H}_2\text{O}$ ), RR of  $15 \pm 2.4$  (range, 10–22 breaths/min), and  $V_T$  of  $611 \pm 75$  (range, 390–700 mL). Delivered  $V_T$  in milliliter per kilogram was  $6.9 \pm 1.30$  and  $V_E$  was  $9.1 \text{ L/min} \pm 1.4 \text{ L/min}$ . Oxygen requirements for desired  $\text{FiO}_2$  and  $V_E$  resulted in a mean oxygen usage of  $3.24 \text{ L/min} \pm 1.87 \text{ L/min}$  (range, 1.6–10.2 L/min). There were 32 changes to  $\text{FiO}_2$ , 18 changes to PEEP, 26 changes to RR, and 20 changes to  $V_T$  during flight. Five patients under-

went no recorded changes in flight. Three desaturation events ( $<90\%$ ) were recorded lasting 35, 115, and 280 seconds. Recorded ventilatory changes averaged less than 1 (0.82) per hour of recorded flight with  $\text{FiO}_2$  being the most common.

**Conclusions:** A computer interface is feasible in the austere aeromedical environment. Implications to military operations and civilian homeland defense include understanding casualty oxygen requirements for resource planning in support of aeromedical evacuation. Portable oxygen generation systems may be able to provide adequate oxygen flow for transport, reducing the need for compressed gas. Future studies of oxygen conservation systems including closed loop control of  $\text{FiO}_2$  are warranted.

**Key Words:** CCATT, En-route critical care, Mechanical ventilation, Autonomous control.

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The modern battlefield has adopted a medical model of en-route combat casualty care.<sup>1</sup> This process necessitates the staged treatment and early evacuation of wounded

and disease stricken service members and civilians in fixed wing cargo aircraft from the battlefield to more established rearward facilities. The United States Air Force Critical Care Air Transport Teams (CCATT) are tasked with the aeromedical evacuation of critically ill personnel, using aircraft of opportunity while providing continuous en-route critical care. To date, all information related to CCATT flights is based on a minimal data set provided by CCATT team members.

The CCATT aeromedical evacuation environment is a challenging one of low light, with significant noise and vibration, and marked barometric pressure changes. Mission duration is often extended with the average mission from Iraq to Germany lasting approximately 6 to 8 hours. As new and more efficient means for aeromedical evacuation are developed, it was our goal to develop a more complete estimation of the mechanical ventilatory needs in flight. This included the evaluation of ventilatory strategies undertaken and the calculation of oxygen requirements during this phase of en-route care. Understanding oxygen requirements is critical to adequate resource planning. The lessons learned from CCATT patient movement in support of OEF and OIF are

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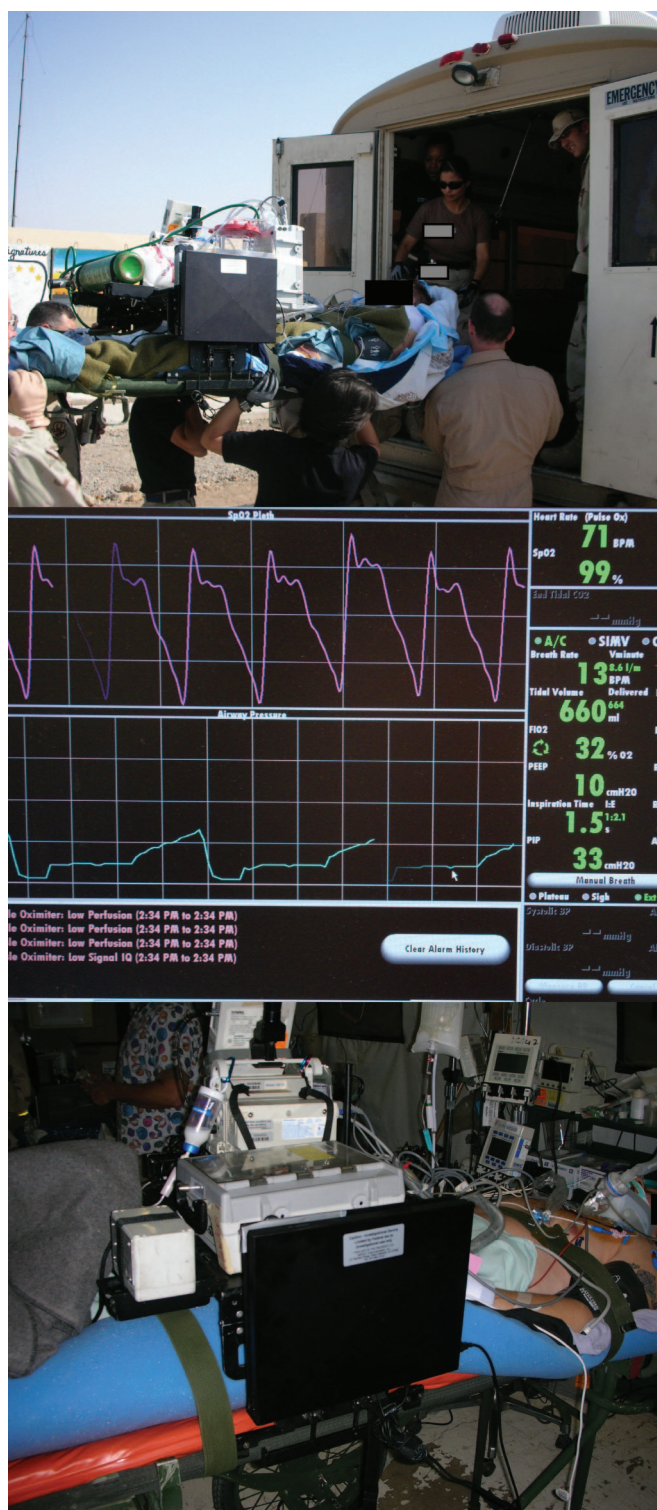
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**Fig. 1.** Data collection device and patient loaded for transport (top), recorded values/screen (middle), data collection computer mounted in Balad ICU (bottom).

applicable to either sustained combat operations or preparation for mass casualty events in homeland defense. An analysis of this data may serve as the basis for future development

of more effective en-route care equipment, improve the training of aeromedical evacuation providers, enable disaster management planning, and improve overall patient safety.

## PATIENTS AND METHODS

Twenty-two patients evacuated by USAF CCAT teams from Balad Air Base, Iraq to Landstuhl Regional Medical Center (LRMC), Germany during the time period of June to September 2006 comprised the patient population. Two of the authors (S.B., J.J.) were deployed to the 332nd Air Force Theater Hospital at Balad Air Base during that time frame and directed data acquisition. Each patient was selected based on the availability of the equipment and their clinical condition necessitating mechanical ventilation during aeromedical evacuation.

The recording equipment used the preexisting RS-232 data port on the Impact 754 ventilator and an integrated pulse oximeter (SpO<sub>2</sub>) attached to each patient. The RS-232 on the power supply of the 754 ventilator continuously provides data regarding ventilator settings and monitored values. This system allowed for the continuous download of heart rate, SpO<sub>2</sub>, ventilator settings, and monitored values every 5 seconds. Data were downloaded and stored via Microsoft Excel spreadsheet on an attached laptop computer. Laptops were mounted to the SMEED litter stand and did not significantly increase the weight or interfere with the CCATT aeromedical evacuation mission (Fig. 1). CCATT teams were not privy to the information and flew their missions with the standard equipment package. Upon completion of each mission the accumulated de-identified data were recovered and stored via a password protected file for further evaluation at completion of the data acquisition phase. No personal health information was collected. The data collection software collected all ventilator settings, airway pressures, heart rate, and SpO<sub>2</sub> (Table 1).

Using date and time of transport, ventilator data were linked to the USAF TRAC2ES and United States Army Institute of Surgical Research (USAISR) Joint Theater Trauma Registry (JTTR) databases for demographic and injury specific data. The University of Cincinnati Institutional Review Board approved retrospective review of this data. Descriptive statistics of average, SD, minimum and maximum values were calculated using Microsoft Excel. Each of the 22 flight downloads were then individually evaluated for episodes of hypoxemia (SpO<sub>2</sub> <90%) and the duration of

**Table 1** Data Collected During Flight

Ventilator Settings	Measured Parameters
Mode	Peak inspiratory pressure
Tidal volume	Mean airway pressure
Respiratory rate	SpO <sub>2</sub>
Minute volume	Heart rate
PEEP	Alarms
FiO <sub>2</sub>	
Inspiratory time	



**Table 2** Demographic, Recorded and Calculated Values During Flight

	Mean $\pm$ SD	Min	Max	Changes En Route
Age (yr)	27 $\pm$ 9.83	19	62	
Weight (kg)	89.5 $\pm$ 12.44	61	127	
ISS 05 (16 of 22)	22.25 $\pm$ 11.13	9	50	
ISS 98 (16 of 22)	24.81 $\pm$ 10.39	9	50	
ISS military (16 of 22)	31.75 $\pm$ 20.63	9	75	
Revised trauma score (16 of 22)	5.95 $\pm$ 1.22	3.36	7.84	
Heart rate (bpm)	98 $\pm$ 20	42	145	
SpO <sub>2</sub> (%)	98 $\pm$ 2	85	100	
FiO <sub>2</sub> (%)	49 $\pm$ 13	24	100	32
PEEP (cm H <sub>2</sub> O)	6 $\pm$ 2.5	0	17	18
Set respiratory rate (bpm)	15 $\pm$ 2.4	10	22	26
Set tidal volume (mL)	611 $\pm$ 75	390	700	20
Avg peak inspiratory pressure (cm H <sub>2</sub> O)	25 $\pm$ 3.82	16.9	31.9	
Avg delivered tidal volume (mL)	610 $\pm$ 78.1	484	719	
Avg delivered tidal volume (mL/kg)	6.94 $\pm$ 1.30	4.96	10.02	
Avg delivered minute ventilation (mL)	9101 $\pm$ 1420	6,765	11,881	
Oxygen requirements (mL/min)	3243 $\pm$ 1857	1,628	10,240	

ISS 05 indicates injury severity score 2005; ISS 98, injury severity score 1998; SpO<sub>2</sub>, pulse oximetry oxygen saturation; FiO<sub>2</sub>, inspired oxygen concentration.

each hypoxic episode recorded. Oxygen utilization was calculated using the average delivered tidal volume and the average FiO<sub>2</sub> for each flight using the equation, Oxygen use =  $([FiO_2 - 21]/79) \times \{MV_E\}$  mL/min.

## RESULTS

All 22 subjects survived transport from Iraq to Germany and the data set included 117 hours of continuous recording. Five patients underwent no recorded ventilatory changes in flight. Three desaturation events (<90%) were recorded lasting 35, 115, and 280 seconds. No interventions were recorded during the desaturation events with spontaneous resolution in all patients. Recorded ventilatory changes averaged less than 1 (0.82) per hour of recorded flight with FiO<sub>2</sub> being the most common (Table 2).

## Demographics

Ages ranged from 19 to 62 years. Nineteen patients had battlefield injuries, 1 patient was involved in a motor vehicle collision not related to combat, and 2 patients had disease-related transports. One patient was a civilian contractor. Of the 20 patients with trauma-related injuries necessitating their aeromedical evacuation, 16 had recorded injury severity score and RTS scores in the USAISR JTTR database. Weight was determined through estimation by caregivers (Table 2).

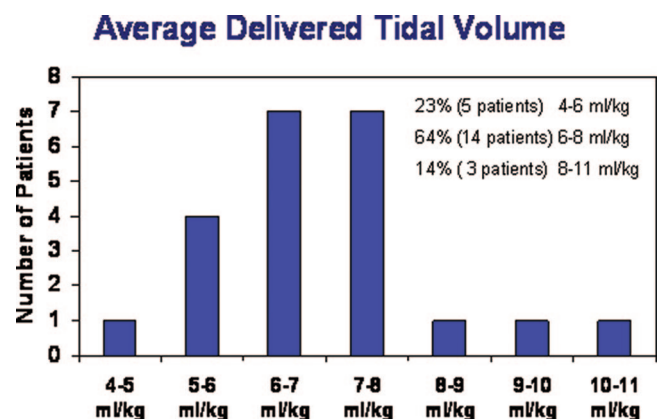
## Tidal Volume/Minute Ventilation

Set tidal volumes (SV<sub>T</sub>) on the Impact 754 ventilator ranged from 390 cc to 700 cc, with an average of 611 cc, and was the third most common change made by CCAT teams en-route averaging 0.17 changes per hour. These correlated with the delivered tidal volumes (DV<sub>T</sub>) of 484 cc to 719 cc, with an average of 610 cc. On a milliliter per kilogram basis, DV<sub>T</sub> ranged from 4.96 mL/kg to 10.02 mL/kg, with an

average of 6.94 mL/kg. Average delivered minute ventilation (DV<sub>E</sub>) was 9.1 L ranging from 6.8 L to 11.9 L (Table 2). The majority of patients in this group (14 of 22; 64%) were managed in the 6 mL/kg to 8 mL/kg range (Fig. 2). Set respiratory rate ranged from 10 breaths/min to 22 breaths/min and was the second most common ventilatory change made by CCAT teams en-route averaging 0.22 changes per hour (Table 2).

## FiO<sub>2</sub>/PEEP/SpO<sub>2</sub>

FiO<sub>2</sub> ranged from 24% to 100% with an average of 49% (Fig. 3). This correlated with a mean SpO<sub>2</sub> of 98%. SpO<sub>2</sub> ranged from 85% to 100%. FiO<sub>2</sub> was the most common ventilatory change made by CCAT teams en-route averaging 0.27 changes per hour. The majority of patients (14 of 22; 64%) were managed with an average FiO<sub>2</sub> in the 40% to 50% range (Table 2). Desaturation was defined as a recorded SpO<sub>2</sub>



**Fig. 2.** Histogram depicting delivered tidal volumes in milliliter per kilogram for all 22 patients during transport.

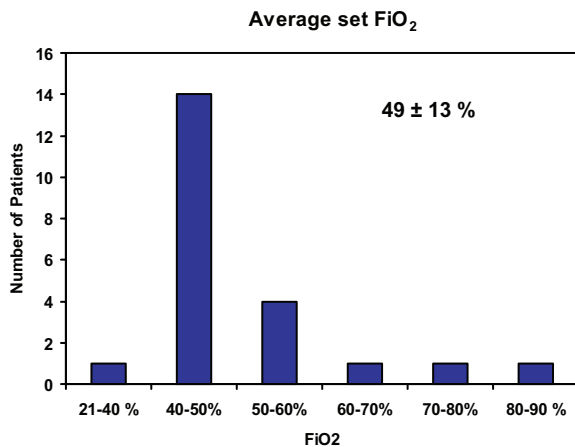


Fig. 3. Histogram depicting set inspired oxygen concentration (FiO<sub>2</sub>) for all 22 patients during transport.

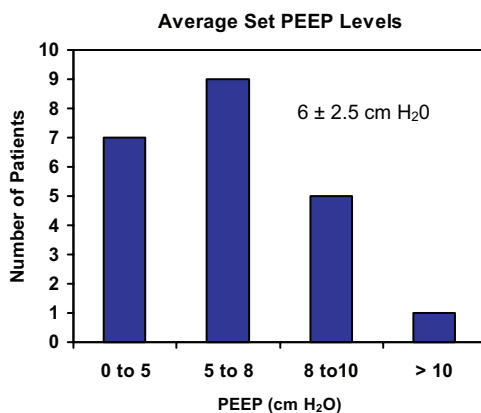


Fig. 4. Histogram depicting set positive end-expiratory pressures (PEEP) in cm H<sub>2</sub>O for all 22 patients during transport.

of less than 90%. The following three episodes were seen: 85% nadir with a 35 second length, 86% nadir with a 115 second length, and an 89% nadir with a length of 280 seconds. No interventions in mechanical ventilation were seen during these desaturation episodes with spontaneous resolution to a SpO<sub>2</sub> of ≥90% in all patients. Positive end-expiratory pressure (PEEP) ranged from 0 cm H<sub>2</sub>O to 17 cm H<sub>2</sub>O. Average PEEP was 6 cm H<sub>2</sub>O with the fewest number of changes made by CCAT teams in route, averaging 0.15 changes per hour (Table 2, Fig. 4).

### Peak Inspiratory Pressure

Peak inspiratory pressures were averaged throughout the missions. Sixty percent of the patient group (13 of 22) averaged between 25 cm H<sub>2</sub>O and 30 cm H<sub>2</sub>O with a range of 17 cm H<sub>2</sub>O to 32 cm H<sub>2</sub>O for the entire group (Table 2). Average peak inspiratory pressure was 25 cm H<sub>2</sub>O during recorded flight (Fig. 5).

### Oxygen Use

Oxygen use was determined using the equation ( $\frac{[FiO_2 - 21]}{79} \times \{MV_E\}$ ) = L/min (l/min). The most common rate of

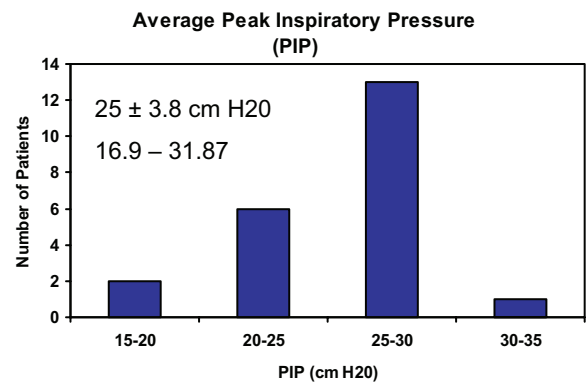


Fig. 5. Histogram depicting peak inspiratory pressures (PIP) in cm H<sub>2</sub>O for all 22 patients.

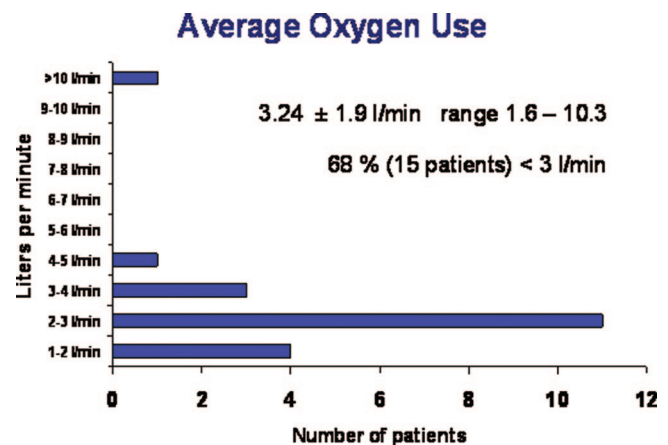


Fig. 6. Histogram depicting oxygen requirements in liters per minute for all 22 patients.

use was 2 l/min to 3 l/min (11 of 22 patients) with 68% patients, (15 of 22) averaging less than 3 l/min (Table 2, Fig. 6).

## DISCUSSION

En-route combat casualty care necessitates the early and rapid evacuation of severely wounded and disease stricken service members and civilians. To our knowledge, this is the first continuous data recording of mechanical ventilation in flight. The battlefield injury patients were significantly wounded with an average ISS98 of almost 25 and ISSMil of 32 (Table 2). The concept of rapidly evacuating such critically injured patients while providing continuous en-route care is unprecedented. Review of outcomes and the experience gained during the duration of the current conflict has demonstrated that the system of en-route critical care is safe and effective resulting in the lowest case fatality rate in the history of modern warfare.<sup>1</sup>

The current study has a number of limitations. Our study was limited to those for whom the Impact 754 was analyzed to be the appropriate means of transport; representing the overwhelming majority of patient transfers, but not, however, capturing the most difficult acute lung injury/ARDS patients.

In the authors' estimation, only 1 in 20 patients are transferred using other forms of mechanical ventilation. This number, however, is not one that can be specifically determined from the existing databases of medical care in support of OEF/OIF. This study is also limited because of software limitations that created data gaps if ventilators were turned off for trouble-shooting. Additional insight might be obtained through a more comprehensive continuous recording of vital signs including hemodynamic and other parameters in addition to the ventilatory parameters monitored in this study. Clinical input regarding patient condition would be valuable in correlating the significance of the observed variations in data. Practice management in PEEP,  $\text{FiO}_2$ , and tidal volume selection is unknown on a broader scale. We do think, however, that this very experienced group of CCATT providers representing a cross-section of medical practice with backgrounds in pulmonary medicine, anesthesia, cardiology, internal medicine, and emergency medicine. With those limitations in mind a number of conclusions can be drawn from the data.

Tidal volume selection was consistent with a lung protective strategy of mechanical ventilation. Tidal volumes were kept below 10 mL/kg with the majority less than 8 mL/kg.<sup>2-4</sup> Weights, however, were merely estimated and ideal weight was not calculated so these values may represent significantly higher values than are seen in the published literature for comparison. Peak inspiratory pressures, however, were low with an average of 25 cm H<sub>2</sub>O and a maximum recorded value of 32 cm H<sub>2</sub>O, suggesting that tidal volume selection was in fact appropriate. Partial pressure of arterial oxygen to  $\text{FiO}_2$  ratios ( $P/F$ ) were not retrospectively calculated for these patients because of the unavailability of blood gases. It might, however, be reasonably assumed that the nature of these combat injuries being battle related and their associated elevated injury severity scores, that each of the subjects were at risk for acute lung injury and the possible development of acute respiratory distress syndrome. When evaluated by the standard ARDSnet tables, only 55% of the patient movements were in compliance with the suggested PEEP/ $\text{FiO}_2$  ratios (Table 3).<sup>2</sup> Underutilization of PEEP was a common observation, with a single patient moved with 0 cm H<sub>2</sub>O PEEP throughout the aeromedical evacuation. Education of CCATT teams should include a review of ideal body weight calculations and PEEP/ $\text{FiO}_2$  as well as tidal volume selection. All patients survived transport and average  $\text{SpO}_2$  was 98%. This is significantly higher than targets set in previously completed studies.<sup>2-4</sup> The addition of significant barometric pressure reductions with a rapid ascent to altitude leaves the CCATT providers estimating what drop in  $\text{SpO}_2$  they will see during the initial ascent. Prior study has documented an average drop in  $\text{SpO}_2$  of 4% in healthy volunteers taken to a cabin altitude of 8,000 feet.<sup>5</sup> Overcompensation for this unknown fall in  $\text{SpO}_2$  is likely the reason for the high-average  $\text{SpO}_2$  in our data set as well as the reason why  $\text{FiO}_2$  is the most common change seen during en-route

**Table 3** Average PEEP/ $\text{FiO}_2$  of Study Patients Compared With the ARDSnet PEEP/ $\text{FiO}_2$

Mission Number	Average PEEP	Average $\text{FiO}_2$	Average $\text{SpO}_2$	ARDSnet PEEP/ $\text{FiO}_2$	Compliance With ARDSnet PEEP/ $\text{FiO}_2$ ?
1	3.44	89	97	14–18	No
2	5.00	50	98	8–10	No
3	6.82	43	98	5–8	Yes
4	7.99	40	97	5–8	Yes
5	3.07	60	99	10	No
6	8	40	99	5–8	Yes
7	5	40	98	5–8	Yes
8	10	50	99	8–10	Yes
9	5.83	57	92	8–10	No
10	8	45	99	5–8	Yes
11	5	40	98	5–8	Yes
12	8.4	76	96	14	No
13	4.91	39	98	5–8	No
14	9.87	41	99	5–8	No
15	4.78	40	99	5–8	No
16	7.01	41	98	5–8	Yes
17	8	59	93	8–10	Yes
18	4.3	47	98	5–8	No
19	0	45	99	5–8	No
20	6	44	99	5–8	Yes
21	2.3	40	98	5–8	Yes
22	5	40	95	5–8	Yes

55% (12 Patients) within ARDSnet  $\text{FiO}_2$ /PEEP recommendations, 41% (9 patients) less than ARDSnet  $\text{FiO}_2$ /PEEP recommendations, 4% (1 patient) greater than ARDSnet  $\text{FiO}_2$ /PEEP recommendations.

care (Table 2). Remarkably, during the 117 accumulated hours of observation there were only three transient episodes of desaturation.

Aeromedical evacuation creates an austere and unique environment that challenges even the most experienced clinician. Medics cannot hear alarms, listen to breath sounds, or maintain normal visual acuity. Situational awareness, therefore, is of paramount importance. We have shown that a computer interface for monitoring is possible in this austere environment. Future areas of potential improvement may link these monitors to closed loop controllers thereby allowing for improved patient safety by providing immediate intervention when monitored values fall below preset targets. One current example under development allows for the autonomous control of  $\text{FiO}_2$  in response to changes in arterial saturation.<sup>6</sup> In the case of our study, a novel autonomous controller may have been able to successfully intervene during the three episodes of observed desaturation. With appropriate automated control the automated response may augment the clinician during periods of lowered situational awareness. With multiple patients such as that which may be seen in a mass casualty event, automation offers the potential to improve safety while allowing minimal number of personnel to safely provide en-route critical care.

Planning for en-route aeromedical critical care evacuation requires resource planning including, most importantly, oxygen supplies. We have shown that nearly 70% of casual-

ties evacuated from this combat support hospital were effectively managed at total oxygen flow of less than 3 l/min. This is a significant observation as currently available commercial oxygen concentrators are capable of providing up to 3 L of oxygen per minute.<sup>7</sup> In a mass casualty event when supplies are usually limited, knowledge of this need would allow for better planning and utilization of resources. CCATT is clearly a model of aeromedical evacuation that would be effective in the event of a mass casualty necessitating the transfer of multiple-injured patients to surrounding hospitals by air.<sup>8-9</sup>

Aeromedical evacuation in opportune cargo aircraft creates a unique environment for en-route critical care. Tactical evacuation creates significant challenges for medical situational awareness and the CCATT/en-route care providers must remain vigilant at all times. We have demonstrated that a computer interface is feasible in this austere environment and may augment situational awareness and provide opportunities to model future care systems that will improve resource utilization and ultimately improve patient safety.<sup>10</sup>

## ACKNOWLEDGMENTS

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## DISCUSSION

**Dr. Evan M. Renz** (US Army Institute of Surgical Research, Fort Sam Houston, TX): It is my privilege to offer a brief review of the article presented by Dr. Barnes and colleagues. This group is to be commended, not only for their recent work, but also for their previous and continued efforts to improve the technology and practice of critical care air transport within the military, which will undoubtedly translate into the civilian medical environment.

The first point I would like the reader to appreciate is the environment in which this work was performed. The actual research process described in this study was performed in the isolated and austere environment of a transport aircraft of opportunity, at altitudes in excess of 30,000 feet, and often in unfriendly skies. This work highlights the fact that clinical research can be, and in fact, should be, conducted in the environments where our most critically injured casualties receive care.

The Methods section makes reference to the Joint Theater Trauma Registry. This is an important point as it emphasizes the joint service applications of their work. The authors' point that their efforts may apply to future homeland defense and disaster plans is worth reiterating.

Next, it is important to appreciate that the authors are reporting information that exists in very few places. There is little scientific data available regarding the subject of ventilator management at altitude and unfortunately the authors have very little historical data from the literature with which to compare their own results. After reading the article, it is clear that this work represents only one early step in a much larger project designed to elevate the state of the art for ventilatory support in flight.

During a four month period they collected dozens of hours of continuous data in 22 critically injured patients as identified by the high injury severity score. During the study the authors noted any and all episodes of hypoxemia, defined as SpO<sub>2</sub> <90%, and the duration of each hypoxic episode recorded. Three brief desaturation events were reported among the 22 patients. I would like to know if they further evaluated the technology and techniques used to place the oxygen saturation detection devices and whether they are satisfied that the brief desaturation events reported were truly reflective of patient hypoxia or simply equipment malfunctions, or related to the aircraft environment. Could redundancy of the pulse oximetry devices help clarify this issue in future trials? The authors noted underutilization of PEEP as a common observation. I would be interested to know why the authors think this occurred and were there any apparent adverse sequelae related to this observation?

This work clearly forms the basis for future investigation to determine whether portable oxygen generation systems may be able to provide adequate oxygen flow for transport systems, reducing the need for large quantities of compressed gases. Such a change could yield high dividends with respect



to both logistics and safety and should be actively pursued. Thank you again Dr. Barnes for sharing this important information with us.

**Dr. Stephen L Barnes** (Division of Trauma and Critical Care, University of Cincinnati, Cincinnati, OH): Thank you, Dr. Renz, for your knowledgeable review of this article. Your experience with the Burn Flight Team gives you unique insight into the process of global aeromedical evacuation. We placed a second pulse oximetry probe on each patient in the study. Although using the same data as the critical care air transport teams (CCATT) would have been ideal, our goal was to record data with as little interference with CCATT operations as possible. We therefore attached a second pulse oximetry probe for collection of heart rate and saturation data. This probe was placed by one of the authors on the ground in Iraq after the CCAT team had packaged the patient

as needed for safe transport. We believe that these desaturation events are real episodes of hypoxemia as all recorded data during the events was continuous and strong, without gaps or interference. The underutilization of PEEP was found in almost 50% of our study based on ARDSnet published values with one patient moved with zero PEEP throughout the mission. This is clearly an education issue that must be addressed in the CCATT community. All patients arrived alive to Germany and our data collection ended at that time. Whether or not repetitive alveolar opening and closure resulted in any adverse sequelae is unknown and would be hard to differentiate from progression of blast injury in this small sample size. Clearly, the exploitation of technology to overcome the shortcomings of this less than friendly environment should be pursued in an effort to improve patient safety.